THE ONSET OF THE COLD HI PHASE
IN DISKS OF PROTOGALAXIES

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ABSTRACT

We discuss a possible delay experienced by protogalaxies with low column density of gas in forming stars over large scales. After the hydrogen has recombined, as the external ionizing UV flux decreases and the metal abundance Z increases, the HI, initially in the warm phase ($T \gtrsim 5000$ K), makes a transition to the cool phase ($T \lesssim 100$ K). The minimum abundance Z_{min} for which this phase transition takes place in a small fraction of the Hubble time decreases rapidly with increasing gas column density. Therefore in the "anemic" disk galaxies, where N_{HI} is up to ten times smaller than for normal large spirals, the onset of the cool HI phase is delayed. The onset of gravitational instability is also delayed, since these objects are more likely to be gravitationally stable in the warm phase than progenitors of today's large spiral galaxies. The first substantial burst of star formation may occur only as late as at redshifts $z \sim 0.5$ and give a temporary high peak luminosity, which may be related to the "faint blue objects". Galaxy disks of lower column density tend to have lower escape velocities and a starburst/galactic fountain instability which decreases the gas content of the inner disk drastically.

Subject headings: galaxies: evolution - galaxies: formation - galaxies: ISM - stars: formation

1. INTRODUCTION

The complexity of the interstellar medium in the inner disk of present-day spiral galaxies (e.g. Kulkarni & Heiles 1988) is in part due to the formation of massive stars: heavy elements in the gas phase and dust have been produced by previous star formation, while present-day massive stars provide a copious input of bulk kinetic energy and of ionizing photons. As a consequence, heating and ionization by the extragalactic photon flux is usually considered unimportant, except in the outermost disks where star formation is absent and where the gas has a low column density and is partially ionized (Maloney 1993; Corbelli & Salpeter 1993a,b; Dove & Shull 1994). In the past, however, before the first substantial burst of star formation occurred, most of the material in protogalaxies was still mainly gaseous and the extragalactic background flux played a very important role in the time evolution and in the transition toward a starburst phase.

The radiative cooling in the earliest phases of the protogalaxy formation was fast for objects with a relatively small virial theorem velocity dispersion (e.g. Rees & Ostriker 1977; Silk 1977). After this initial transient and before extensive star formation starts, the quasi-steady state ionization and thermal balance depends on the extragalactic ionizing flux. Proto-galaxies with small column densities of gas (e.g. dwarf galaxies) may experience a delay in the recombination of ionized hydrogen until this flux has dropped below a certain value (Babul & Rees 1992; Efstathiou 1992). In the present paper we consider the next evolutionary phase for disk galaxies, where the circular rotation velocity V_r accounts for most of the virial velocity dispersion and remains constant. We shall estimate the further cooling (during this phase and after the hydrogen has recombined) assuming that the changing sound speed v_s satisfies $v_s \ll V_r$. This ensures that we can use a slab approximation with gas column density unchanged during the cooling process (although the scale height decreases). Evidence for rotationally supported disks at redshifts $z \sim 2-3$ is given for example by Wolfe *et al.* (1994).

For a volume of predominantly neutral hydrogen gas with solar metal abundance, a given thermal pressure P and a given ionization rate ξ per neutral H-atom, the equilibrium gas temperature depends on the ratio P/ξ. Field, Goldsmith, & Habing (1969) showed that over a narrow range of values of P/ξ two phases of HI can coexist: a warm phase at $T \sim 10^4$ K and a cool phase at $T \sim 100$ K. A third phase found at intermediate temperatures ($T \sim 3000$ K) is thermally unstable. For larger (smaller) values of P/ξ only the cold (warm)

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phase exist. For a given P/ξ the equilibrium temperature depends also on the abundance Z of heavy elements (throughout this paper given in units of solar abundances) and there would not be a range of P/ξ with coexisting phases if $Z = 0$. We shall consider medium-small values of Z, e.g. a slow build-up of metals with time during this phase, from $Z \sim 10^{-4}$ to $Z \sim 0.1$. This assumption of slow, sporadic metal injection is discussed in Section 2. We will analyze in detail the possibility that after the hydrogen has recombined, some proto-disks experience a warm to cool phase transition before violent star formation turns on over large scales. At which redshift this phase transition occurs depends quite sensitively on the metallicity Z, on the intensity and evolution of the extragalactic background and on the neutral hydrogen column density N_{HI}. Since in ordinary disk galaxies N_{HI} varies radially and with galaxy type, we shall consider slabs with gas distribution whose maximum gas column density before star formation takes place, N_{max}, varies from $\sim 10^{22.5}$ cm^{-2}, as for ordinary large spiral galaxies, to values ten times smaller $\sim 10^{21.5}$ cm^{-2}. The latter is of interest for extreme dwarf irregular galaxies and for putative "Cheshire Cat" galaxies (see Section 4 and Salpeter 1993) where N_{max} is small but the radial scale-length for $N_{HI}(R)$ may not be small.

The external radiation field (UV and X-ray background at a given redshift) and the structure of the protogalactic disk are discussed in Section 2. The main numerical results for the cooling from the warm HI phase to the cool phase as function of the background flux intensity, z, Z and N_{HI} are given in Section 3. We shall see that results depend weakly on the dark matter column density, on the gas radial scalelength and on the rotation velocity V_r except for cases with small values of both N_{max} and V_r.

The motivation for studying the transition of a proto-disk from the warm to the cold HI phase is two fold: (i) temperature measurements are becoming available for the HI in damped Lyα absorbers at intermediate redshifts (e.g. $z = 0.69$, Cohen et $al.$ 1994). These systems are likely to be proto-disks of some kinds of galaxies and it is of interest to know whether finding warm HI must imply the presence of young massive stars or whether it might merely be a proto-disk before the phase transition. (ii) Observations of faint blue galaxies at intermediate redshifts ($z \sim 0.5$), but not at low z have led to speculations that a catastrophic first starburst may have occurred with a consequent galactic wind and substantial mass loss. In Section 4 we present speculations on an accelerating starburst cycle which can lead to such mass loss. We shall show that such phenomena are likely to occur in disks with small column densities of gas, but not in proto-galaxies which are the

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progenitors of today's large spiral galaxies.

2. PROTOGALACTIC DISKS AND THE EXTERNAL RADIATION FIELD

2.1-The extragalactic radiation field.

The UV and X-ray extragalactic background at a given redshift z_{obs} depends on the sources of UV and X photons at $z > z_{obs}$ and on the number of intervening systems like Lyα clouds and Lyman Limit systems (see Section 4). The overall space distribution of quasars and their luminosity function and contribution to the UV and X-ray background are still subject of controversy (e.g. Bechtold *et al.* 1987; O'Brien, Gondhalekar, & Wilson 1988; Hartwick & Schade 1990). We shall be interested only in redshifts $z \lesssim 2.5$, where quasars account for either an appreciable fraction or most of the ionizing flux (Irwin, McMahon, & Hazard 1991; Warren, Hewett, & Osmer 1991). The proximity effect at $z \sim 2$ gives a flux value at the Lyman edge $J_{21} \gtrsim 0.3 \times 10^{-21}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} but we are interested in higher photon energies ($E >$100 eV) for penetrating and heating protogalactic clouds with HI column densities $\gtrsim 2 \times 10^{20}$ cm^{-2}. In this spectral region there are still uncertainties regarding both the intrinsic emission spectrum and the attenuation by intervening clouds (Madau 1992; Miralda-Escude & Ostriker 1992; Meiksin & Madau 1993).

Since photon energies of interest are above 54 eV, the resulting background spectrum after absorption by intervening systems depends mainly on the HeII abundance in these systems: the total intervening average neutral hydrogen column density of a few times 10^{19} cm^{-2} comes mainly from the Lyman limit systems which have individual column densities $> 10^{17.2}$ cm^{-2} and are overwhelmingly neutral. The overall He/H abundance ratio by number is only ~ 0.1, the total intervening He column density is therefore only a few times 10^{18} cm^{-2} and the HeII column density is even less. However, the uncertainties are much greater for the intervening Lyα forest systems (which individually have $N_{HI} < 10^{17.2}$ cm^{-2}) because the hydrogen is mainly ionized but the value of the large ratio N_{HII}/N_{HI} depends of the physical model for these clouds in addition to the original, unabsorbed background spectrum (Miralda-Escude & Ostriker 1992; Giallongo & Petitjean 1994; Madau & Meskin 1994). For example, for models with very low external pressure and little dark matter, the ratio N_{HII}/N_{HI} can exceed 10^4, He is fully ionized and $N_{HeII}/N_{HI} \sim 10^3$. In those cases the helium opacity due to Lyman-α forest can be large and important for the resulting

shape of the background spectrum. On the other hand models which favor a high pressure for the forest clouds with $N_{HII}/N_{HI} < 10^3$, must have $N_{HeII}/N_{HI} < 100$ and a small attenuation of the background above 54 eV.

Given the uncertainties in the attenuation of the background spectrum we shall introduce an adjustable multiplying factor J_0 for the intensity of the background flux. As reviewed by Hartwick & Schade (1990) and by Boyle, Shanks, & Peterson (1988) the quasar flux decreases with time for redshift $z \leq 1.5$ and we shall use the following simple formula for energies above 100 eV, which approximates the spectral shape after absorption by HeII (Madau 1992) and is consistent with a decrease of the spectral index as we approach the hard X-rays spectrum ($\alpha = 0.4$ for $E \geq 1.5$ keV):

$$ J(\nu, z) = 3 \times 10^{-25} J_0 \left(\frac{\nu}{100 \text{ eV}}\right)^{-1} (1 + \bar{z})^3 \text{ ergs s}^{-1}\text{cm}^{-2}\text{sr}^{-1}\text{Hz}^{-1} \qquad (2.1) $$

with $\bar{z} = 1.5$ for $z > 1.5$ and $\bar{z} = z$ otherwise. For $J_0 \simeq 1.2$ the above expression is close to Madau's estimate above 100 eV but given the uncertainties mentioned above this value of J_0 might underestimate the real flux and the range of J_0 we shall consider is $1 \leq J_0 \leq 5$. Another important flux of interest is the UV flux for ionizing carbon (11.26 eV) since CII (158μm) is the most important cooling transition in the cool HI phase. The quasar contribution to these energies is slightly higher than at the Lyman edge and a further contribution can derive from star-forming galaxies. We shall show that even the lower limit to the UV flux is already sufficient to keep the carbon singly ionized.

2.2-Geometry for protogalactic disks.

We consider only objects which evolve into protogalactic disks with circular rotational velocity in the range 30 km s^{-1} < V_r < 300 km s^{-1} and with nucleon column density N_g (normal column density of gas above and below the plane, by number, hydrogen plus four times that of helium) whose maximum values N_{max} [$N_g(R = 0)$] is $10^{21.5} \lesssim N_{max} \lesssim 10^{22.5}$ cm^{-2} before large scale star formation starts. Giant spiral galaxies occupy the upper end of both ranges, extreme dwarf irregulars the bottom end, and the ranges also cover the putative "Cheshire Cat" galaxies (Hoffman *et al.* 1993; Salpeter & Hoffman 1995) before starburst induced galactic winds decrease N_{max} further (see Section 4). As discussed before (Gott & Thuan 1976; Rees & Ostriker 1977; Dekel & Silk 1986; Chiba & Nath 1994) radiative H and He cooling can lead to a partially ionized, but predominantly neutral, gas with temperature ~ 1 to 3×10^4 K in less than a Hubble time t_H, at redshift $z \sim 2.5$. The isothermal sound speed is thus at most $v_s \equiv \sqrt{kT/\mu m_H} \sim (7 \text{ to } 15)$ km s^{-1} (k is

the Boltzman constant) and we have the inequality $v_s \ll V_r$ (only barely at the lower end of the ranges). This inequality ensures that the vertical scaleheight $x_{1/2}$ of the galactic disk is small compared with the galaxy radial scalelength. The protogalaxy is therefore rotationally supported against gravitational collapse. Hydrostatic equilibrium at each radius R is possible due to thermal pressure support against gravitational attraction. We assume the above inequality throughout this paper, so that the total column density of gas and $V_r(R)$ do not change with time, even though the temperature $T(R)$ and $x_{1/2}(R)$ decrease with time as the gas cools further.

We define the gas vertical scale height $x_{1/2}$ as the height above the midplane such that half of the total gas mass per unit area lies between $+x_{1/2}$ and $-x_{1/2}$. To estimate the total gas pressure at $x_{1/2}$ we can write the approximate simple formula assuming an almost spherical halo of dark matter:

$$\frac{P_{1/2}(R)}{k} \simeq \frac{P_{ext}}{k} + \frac{\pi G m_H^2}{2.6k} N_g^2(R) \Big\{ 1 + \eta(R) \Big\} \mathrm{cm}^{-3} \mathrm{K} \qquad (2.2)$$

$$\eta(R) \equiv \frac{N_{dm}(R)}{N_g(R)} \frac{v_s(R)}{V_r(R)} \qquad (2.3)$$

where G is the gravitational constant, N_g is the total column density of nucleons and N_{dm} is the column density of dark matter, defined as the total dark matter mass per unit area divided by the proton mass m_H.

We assume a roughly exponential form of $N_g(R)$ in the inner disk, so that much of the total mass is contributed by regions where $N_g \sim e^{-2} N_{max}$ to N_{max}. We disregard the very innermost scalelength because of possible complications from a nuclear bulge or AGN activity and consider only radii where $N_g \sim (0.1 \text{ to } 0.3) N_{max}$, so that $N_g > 10^{20.5} \mathrm{cm}^{-2}$ throughout. The pure gas self gravity term in equation [2.2] thus exceeds 200 cm^{-3} K whereas $P_{ext}/k \lesssim 15$ cm^{-3}K for $z \lesssim 2.5$ (e.g. Charlton, Salpeter, & Linder 1994). We therefore omit P_{ext} entirely in eq. [2.2]. Some local external pressure might not be completely negligible if ram pressure is present with a consequent infall of hot material which confines the disk; for these hypothetical cases the effect on $P_{1/2}$ to a first approximation can be considered by choosing a slightly higher value of η. For the inner disk of regular, bright spiral galaxies the ratio $N_{dm}/N_g \lesssim 1$ (Persic & Salucci 1990) and $V_r > 100$ km s$^{-1} > v_s$, so that the second term in bracket in eq. [2.2] can be omitted entirely. However towards the most extreme dwarf irregular galaxies N_{dm}/N_g increases (roughly as $L^{-0.7}$) and V_r decreases so that η in eq. [2.3], becomes appreciable. In most of this paper we

consider $(1 + \eta)$ as a constant, so that $P_{1/2}$ appears proportional to N_g^2 and independent of temperature T. The possible temperature-dependent pressure enhancement for extreme dwarfs is briefly discussed in Section 3.3.

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2.3-The gravitational instability.

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For a rotating disk with thickness less than the radial scalelength, the criterion for gravitational stability does not depend strongly on the thickness (Goldreich & Lynden-Bell 1965b). We therefore consider only the "Toomre criterion" for an infinitely thin disk and arbitrary rotation law $V_r(R)$. The condition for the gravitational instability depends on the gas velocity dispersion which, in the absence of random motion and for an isothermal slab, equals the sound speed v_s defined in the previous subsection. The condition for instability can be written as (Toomre 1964; Goldreich & Lynden-Bell 1965a; Binney & Tremaine 1987):

$$N_g(R) \gtrsim N_g^{crit}(R) \equiv \frac{\kappa(R)v_s(R)}{\pi m_H G} \tag{2.4}$$

where the epicyclic frequency κ is

$$\kappa(R) \equiv 1.41 \frac{V_r(R)}{R} \left[1 + \frac{R}{V_r(R)} \frac{dV_r}{dR} \right]^{1/2} \tag{2.5}$$

If the dark matter has an isothermal distribution, $N_{dm}(R) \propto R^{-1}$, the rotation law is given by

$$V_r^2(R) = \pi m_H G R \left[\frac{4}{\pi} N_{dm}(R) + \bar{N}_g \right] \tag{2.6}$$

where $\bar{N}_g$ is the mean gas column density inside a radius R. Since we are mostly interested in $R \sim$ (1 or 2) radial scalelength R_l, where $V_r(R)$ varies slowly, the bracket in eq. [2.5] can be replaced by unity and the inequality [2.4] can then be rewritten in a dimensionless form

$$\frac{N_g^{crit}(R)}{N_g(R)} \equiv 1.41 \frac{(4/\pi)N_{dm}(R) + \bar{N}_g}{N_g(R)} \frac{v_s(R)}{V_r(R)} \lesssim 1 \tag{2.7}$$

Instability first sets in when N_g^{crit}/N_g is less than unity. In regular spiral galaxies at $R \sim$ (1 or 2)R_l, N_{dm} is not much larger than N_g (Persic & Salucci 1990), $1.4v_s < 30$ km s$^{-1} \ll V_r$, and the the instability criterion is satisfied as soon as the transient radiative cooling is over and the hydrogen has at least partially recombined. At some larger radius $N_g(R)$ drops

below the critical value for instability (Kennicutt 1989), since $N_g \propto e^{-R/R_l}$ whereas N_{dm} decreases only as R^{-1}, but in this paper we consider only the inner disk. However, for dwarf irregulars and for the putative "Cheshire Cat" galaxies V_r, N_g, N_{dm}, and $N_g(R_l)/N_{dm}(R_l)$ are all smaller although it is not clear what $N_g(R_l)/N_{dm}(R_l)$ is. For either or both these classes of galaxies we may have the following situation: when the hydrogen first recombines but is still in the warm phase, $v_s \sim 7 - 15$ km s^{-1} and $N_g(R_l)$ may be below the critical value for instability, but in the cool phase $v_s \lesssim 1$ km s^{-1} and the instability condition in eq. [2.7] may be satisfied. Thus low surface brightness objects which are less opaque to the background radiation and have a lower rotational speed become gravitationally unstable and collapse later, only when the slab makes a transition to the cold phase. As a result the star formation epoch in dwarf galaxies is delayed and, as we shall see, it may become much more violent than in normal spiral galaxies.

2.4-The metal abundance.

This paper will be concerned directly with the onset of a systematic gravitational instability in the disk and of a massive starburst plus galactic fountain activity, producing metals. However, we have to make some assumptions about a possible slow and minor buildup before this bulk star formation starts suddenly. The presence at high redshifts of quasars and AGN is likely to have given some metal contamination early. The extended metal line absorption systems (which are likely to be associated with galaxies, see Section 4) suggest in fact that some metals appeared in a nuclear bulge and halo before any star formation in the proto-galaxy disk. We shall start our disk calculations with an initial $Z \sim 10^{-4}$, rather than metal-free gas. Early metal contamination is not likely to have been more than 10^{-3}, as seen from the small number of present-day halo stars with $Z \lesssim 10^{-3}$ (Spite & Spite 1992; Norris, Peterson & Beers 1993).

Most galaxies have smaller companions, and minor gravitational interactions could move parcels of gas to increase gas column density in a small fraction of the disk, resulting in some very localized star formation. Moreover present-day dwarf irregular galaxies have typical abundances of $Z \lesssim 0.1$, but very few star-less dwarf proto-galaxies are known today, even though they would be easy to detect in HI emission (e.g. Briggs 1990; Hoffman, Lu, & Salpeter 1992). This suggests that very small bursts of star formation (processing, say, 10^{-4} or 10^{-3} of the gas into stars) were fairly common. We therefore make the following assumptions: our explicit calculations for a gas slab are for constant column density (no explicit external interference), but we allow the metal abundance Z to increase slowly with

time (to mimic the sporadic mini-starbursts).

We assume a helium abundance by number of 0.1, so that the total column density of nucleons is $1.4N_H$. The metal species considered are carbon, iron, oxygen, nitrogen, silicon, and sulfur with abundance ratios Z relative to solar. We have assumed that the ionized to neutral ratio for oxygen and nitrogen are the same as for hydrogen to account for charge exchange effects. There is a sufficient number of photons below 13.6 eV to keep carbon, iron, silicon and sulphur singly ionized. For example the condition for carbon to be all singly ionized is:

$$\frac{P}{k} \ll 1.3 \frac{\xi_C}{10^{-12}} \frac{100 \times T^{1.8}}{Z} \tag{2.8}$$

the contribution to the carbon ionization rate, ξ_C, from the quasars alone at $z \sim 2$ and at 11.6 eV gives $\xi_C \sim J_0 \times 10^{-12}$ s^{-1} and hence the above condition at $T = 100$ K for example, is satisfied as soon as $P/k \ll 5 \times 10^5 J_0/Z$ which we shall see is always true. Since in this paper we study the evolution of proto-disks before a large scale star formation takes place and assume a relatively low values of Z, we neglect dust grains and their possible contribution to gas heating.

3. THE TRANSITION FROM THE WARM TO COOL HI PHASE

We are interested in the structure of a slab, as a portion of a protogalactic disk, with a fixed value of the gas column density N_g. The vertical equilibrium of the slab changes with time because the incident ionizing flux $J_0(1 + \bar{z})^3$ in eq. [2.1] decreases for redshifts lower than $z = 1.5$ and the metal abundance Z is assumed to increase with time. Although we do not specify the rate of increase in Z (due to sporadic star formation elsewhere), changes in flux and in Z decrease the heating and increase the cooling, so that the equilibrium temperature of any gas parcel decreases with time. The gas stays warm and partially ionized until a certain epoch which depends on N_g both through the pressure term and through the opacity which the slab offers to the external UV radiation. We consider only values of $N_g \gtrsim 10^{20.5}$ cm^{-2} and $J_0(1 + \bar{z})^3 \lesssim 200$, in which case the ionized layer at large heights x contains little mass. For given values of N_g, z and Z, the pressure $P(x)$ increases with decreasing height x and the surviving ionization rate $\xi(x)$ decreases because of absorption by matter above x. The temperature therefore decreases with decreasing

x and also with increasing time. Because cooling rates are finite, there is a time-delay between temperature actually achieved and the thermal balance equilibrium temperature. This delay is discussed in Section 3.2; we first calculate equilibrium temperatures for fixed values of Z and z.

3.1-The transition point for the two-phase equilibrium.

At first (large z, small Z) most of the hydrogen is in the warm HI phase. In the absence of any metals there is just a single phase medium and the gas temperature hardly gets much below 5000 K, but with even a small amount of metals a two phase medium becomes possible. We shall call "transition point" the lowest equilibrium temperature for which the warm phase is thermally stable. In principle, for a slab of uniform composition the sharp transition between the warm and the cool phase starts in the midplane ($x = 0$) and moves up as Z increases and z decreases. In this paper we shall consider only the evolution of a single characteristic parcel of gas at height $x_{1/2}$. The total gas pressure for this parcel of gas, $P_{1/2}$ as given by eq. [2.2] is a good approximation in the warm phase since the gas is quite uniform in temperature. Our numerical calculations show, moreover, that the transition between a uniform warm slab and a cold slab, where most of the gas is at temperature 30 K, is quite sharp: once a cold core forms the warm atmosphere which is left above is small and therefore $P_{1/2}$ is again a good approximation. For an accurate time dependent calculation we have the complication that η decreases with time as $\sqrt{T}$ but in this subsection we consider $(1 + \eta)$ as a constant factor.

Background photons are responsible for the ionization-recombination balance of the hydrogen and helium gas. Secondary electrons are included as well and the on the spot approximation is used. Close to the transition point the hydrogen gas is mostly neutral, and therefore for the photon energies which are of interest, helium is singly ionized with fractional ionization 3 times that of hydrogen. We keep track of corrections for ionization in an explicit calculation but N_{HI} is close to the total hydrogen column density, and the photon absorption, which depends strongly on N_{HI}, changes little with time. Heating due to photoionization of H and He by background radiation is balanced by radiative cooling via CII, SiII, FeII, OII, OI, NI, HI lines. At very low temperatures ($T < 50$ K) additional heating comes from carbon photoionization. The expression for energy losses due to collisional excitation of line radiation have been taken from Dalgarno & McCray (1972) except for the fine structure excitation of CII and OI by atomic hydrogen impact, for which we have used the results of Launay & Roueff (1977), and for the Ly-α excitation of neutral

hydrogen for which we refer to Spitzer (1978).

In Figure 1 we show two examples of the curve which determines the equilibrium between the phases (Field et $al.$ 1969). In principle the equilibrium temperature T is a function of the ratio of $P_{1/2}$ to photoionization rate per atom $\xi_{1/2}$, but since we have fixed the HI column density in order to compute the absorption of the UV flux, the ratio $P_{1/2}/(1 + \eta)$ of each slab is fixed and $\xi_{1/2}$ for a fixed spectral index α depends linearly on the intensity $J_0(1 + \bar{z})^3$ of the incoming radiation. For $N_{HI} = 3 \times 10^{20}$ and $N_{HI} = 3 \times 10^{21}$ cm^{-2} the ratio $P_{1/2}/(1 + \eta)$ is ~ 200 and ~ 20000 cm^{-3} K respectively. In Figure 1 the vertical axis increases downward and gives $J_0(1 + \bar{z})^3/(1 + \eta)$ required to result in the equilibrium temperature T, for a single value of Z and two values of N_{HI}. The region where $J_0(1 + \bar{z})^3/(1 + \eta)$ increases with increasing T is thermally unstable (Field 1965; a complete analysis of the thermal stability in a photoionized medium is given by Corbelli & Ferrara 1995). The circle on each curve denotes the transition point, the minimum value of temperature, T_{tr}, for which the stable warm phase exists. Here the most important metal line cooling comes from FeII. The equilibrium in the cold phase which corresponds to the same value of $[J_0(1 + \bar{z})^3/(1 + \eta)]_{tr}$ has instead a cooling function dominated by the CII (158μm) line excited via H impact.

We can display the transition point (for given values of z and $J_0/(1 + \eta)$) in terms of a function Z_{tr} of N_{HI}: Z_{tr} is defined as the value of the metal abundance Z needed for the equilibrium temperature to be equal to the transition temperature. We have carried out numerical calculations of Z_{tr} in full thermal equilibrium, for a number of values of the various parameters and for the assumed spectral index $\alpha = 1$ in eq. [2.1]. If one had assumed a steeper spectrum the resulting Z_{tr} would depend even more strongly on N_{HI}. Let t_{heat} and t_{cool} be the heat content divided by the photon heating rate and radiative cooling rate, respectively, at the transition temperature $T_{tr} \lesssim 8000$ K (shown by the circles in Figure 1 for two values of N_{HI}). At equilibrium $t_{heat} = t_{cool}$; t_{cool} is proportional to the inverse of the volume density, $1/n$, and also approximately to $1/Z_{tr}$ since metal line cooling is important below 8000 K. Although $1/n$ decreases with increasing N_{HI}, t_{cool} actually increases due to the stronger attenuation of the background flux with a consequent decrease both of Z_{tr} and of the cooling rate at transition (T_{tr} decreases with N_{HI}). In Section 3.2 we discuss the value of $Z(N_{HI})$ needed in order to have a fast warm/cool phase change.

3.2-Time delay for the actual transition.

For values of $J_0(1+\bar{z})^3/(1+\eta)$ slightly smaller than the transition value, both stable phases

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are in principle possible. Under some circumstances it may not be obvious which phase is actually present, but there is no controversy for the evolution we consider here: since Z (and therefore cooling) increases with time and the ionizing flux decreases, the equilibrium temperature decreases monotonically with time. For the actual temperature $T(t)$ to be able to decrease with time, cooling must exceed heating slightly, i.e. the temperature must be slightly larger than the equilibrium value. The actual temperature $T(t)$ can never cross the equilibrium curve illustrated in Figure 1 and will remain to the right of the warm phase portion of the curve until the transition point is reached. We can then ask how big the time delay is, as a function of z and N_{HI} in order to complete the phase transition. We have also investigated the time delay in recombination: the recombination time t_r decreases with increasing column density but it stays always much smaller than t_H for $N_{HI} > 10^{20.5}$ cm^{-2}. The Hubble time t_H, at redshift z, is defined as:

$$t_H = 2.06 \times 10^{17} \frac{100 \text{km s}^{-1} \text{Mpc}^{-1}}{H_0} (1+z)^{1.5} \text{s} \tag{3.1}$$

where H_0 is the present value of the Hubble constant (we use $H_0 = 75$ km s^{-1} Mpc^{-1} in the rest of this paper).

We compute the cooling curve at transition, keeping J_0, η and z fixed, but perturbing the value of the metallicity to a value $Z > Z_{tr}$. During the isobaric transition from the warm to the cool phase, the volume density n, x and T evolve with time. We call t_{tr} the total time required to complete this transition from $T = T_{tr}$ to the final temperature $T = T_f$. For $z = 1$, $J_0 = 1$, $\eta \ll 1$ and $N_{HI} = 4 \times 10^{21}$ cm^{-2} we show as an example in Figure 2 the actual cooling curve given a perturbed value of metallicity $Z = 2Z_{tr} \simeq 3.2 \times 10^{-4}$. For this case t_{tr} is slightly larger than t_H, which in other words means that one should have $Z \gg Z_{tr}$ in order to have a rapid cooling to the cool phase. Figure 3(a) gives the ratio of t_{tr} to the Hubble time t_H as a function of N_{HI}. The open circle marks the case shown in detail in Figure 2 and the star marks the column density, N_*, where $t_{tr}/t_H = 0.2$. We shall talk of "rapid cooling" when $t_{tr}/t_H \leq 0.2$ and define Z_{min} for a chosen value of N_{HI} as that value of Z which gives $t_{tr}/t_H = 0.2$. In other words we do the following trial and error process: we guess a value of Z above Z_{tr} and carry out a time dependent heating/cooling calculation numerically, starting at a temperature $T = T_{tr}$ keeping Z, J_0, and z fixed during the integration. Since $Z > Z_{tr}$, cooling exceeds heating already and the imbalance increases as T decreases monotonically with time. Keeping the pressure constant during the cooling process we note the actual time taken for T to reach the cool phase, t_{tr}, we

adjust the value of Z until $t_{tr} = 0.2t_H$ and call Z_{min} this value of Z. For $Z \sim Z_{tr}$ we have seen that t_{cool} increases with N_{HI}, therefore in order to have a fast warm/cool phase change the metallicity should increase by a larger factor with respect to $Z_{tr}(N_{HI})$ as N_{HI} increases. Due to the strong decrease of Z_{tr} with N_{HI} the resulting Z_{min} still decreases with N_{HI}. In other words, if we keep constant the cooling time, the increase of volume density with N_{HI}, due to self gravity, is strong enough to require decreasing Z_{min} values with increasing N_{HI}. In Figure 3(b) $Z_{min}(N_{HI})$ is shown as a thick curve and $Z_{tr}(N_{HI})$ as a thin one. The ratio $(Z_{min} - Z_{tr})/Z_{tr}$ increases with N_{HI} and we mark with a star the column density N_* where $Z_{min} = 2Z_{tr}$. While Z_{tr} depends only on the ratio $J_0/(1 + \eta)$, Z_{min} depends on J_0 and η separately since it is directly related to the cooling time.

In Figure 4 we give the main results of this paper, namely Z_{min} as a function of N_{HI} for various J_0, η and z. For each case we again mark with a star the column density where $Z_{min} = 2Z_{tr}$. Consider first values of N_{HI} appreciably less than N_* at a time when Z has increased to just above $Z_{tr}(N_{HI})$: in this case a slight further excess of Z above Z_{tr} will ensure that the phase transition proceeds all the way to the cool phase in a fraction of the Hubble time. By contrast, consider a case of $N_{HI} > N_*$, e.g. $N_{HI} = 6 \times 10^{21}$ cm^{-2} for $J_0 = 1$, $\eta << 1$, and $z \sim 2.5$. Here Z_{tr} would be only 10^{-5}. But cooling proceeds slowly for these larger column densities since Z will have to increase by at least a factor 10 above Z_{tr} (to a value close to Z_{min}) in order to cool rapidly below 100 K. However if, as in this case, Z_{min} is less than the likely initial abundance Z_{init}, the whole cooling process happens as soon as the gas recombines.

As the redshift decreases below 1.5 different column densities will change phase at different redshift due to the decreasing intensity of the background flux. For example if $J_0/(1+\eta) = 5$, and $Z \sim 0.01$, does not change with time between $z = 1.5$ and $z = 0$ all slabs with N_{HI} between 5×10^{20} and 10^{21} cm^{-2} will undergo the phase transition.

3.3 - Time dependence of dark matter gravity.

The dimensionless factor η in eq. [2.2] and [2.3] represents the contribution to gas pressure made by dark matter gravity. As the gas cools its vertical scale height decreases, even if the dark matter distribution is unchanged. As the height $x_{1/2}$ decreases less dark matter resides below the layer and η decreases roughly as $v_s \propto \sqrt{T}$ in eq. [2.3]. In an accurate time-dependent cooling calculation one should therefore consider the time dependence of η. In Figure 4 we show results for a large and fixed value of η, evaluated at a fixed temperature, lower than T_{tr} and intermediate between the warm and cool phase temperatures, say

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$T \sim 2000$ K. To compute approximately the transition time, we use the prescription of Section 3.2 referring mainly to the epoch when the warm phase of HI has gone thermally unstable and the temperature has dropped a little below the equilibrium value at the last stable point.

For giant spiral galaxies with large V_r the factor η is not too large, but can be quite appreciable for dwarf irregular and "Cheshire Cat" galaxies, at least while the HI is in the warm phase. Cases where η starts large and decreases to small values as the HI cools are of particular interest in Section 4, since the dimensionless ratio in eq. [2.7] is of the same order of magnitude as η and its decrease is of interest for the gravitational instability. Cases where N_g^{crit}/N_g starts a little larger than unity and decreases might be gravitationally stable in the warm phase and unstable in the cool phase: these cases will have η not much smaller than unity and varying and its value cannot be neglected in the pressure equation. With $(1 + \eta)$, and hence the gas pressure $P_{1/2}$, decreasing as the gas cools, the cooling history is more complex than the description in Section 3.2, but not qualitatively different: the cooling rate (per H-atom) depends on gas density $n \propto P/T$ which can be written in the form $n \propto (T^{-1} + bT^{-1/2})$ and increases with decreasing T whether the second term dominates or not. The correct cooling rate thus increases more slowly as T decreases appreciably. While $J_0(1 + z)^3$ and Z both evolve in a direction so as to accelerate the cooling transition, the decrease in $(1 + \eta)$ decreases the pressure and hence tends to slow down the cooling somewhat.

4. A POSSIBLE STARBURST/GALACTIC FOUNTAIN INSTABILITY:

RELATIONS TO QSO ABSORPTION LINES AND TO FAINT BLUE GALAXIES

This paper deals directly only with the inner gaseous disks of protogalaxies, but their evolution is related to the faint blue galaxies found at intermediate redshifts, and to Ly-α absorption clouds provided by the outer galaxy extensions. Quasars were already present at very early cosmological epochs (redshifts $z > 4$) and Lyα and metal absorption lines have been observed over a broad range of redshifts and column densities. Three ranges of neutral hydrogen column densities are particularly well studied, the "Lyα forest" with $N_{HI} \gtrsim 10^{14}$ cm^{-2}, the "Lyman Limit systems" (LLS) with $N_{HI} > 10^{17}$ cm^{-2} and the "damped wing systems" with $N_{HI} > 10^{20}$ cm^{-2}. The damped wing systems are usually associated with the inner disks of protogalaxies, already rotationally supported at $z \sim 2$

to 3. At least for large spiral protogalaxies, the star formation and metal abundances in the inner disk at that epoch were probably at an intermediate evolutionary stage: In one well-documented case at $z = 2.3$, for instance (Wolfe et al. 1994), metal-production by massive stars had reached about 10% of the present-day Galactic value. The LLS (e.g. Bergeron & Boissé 1991; Lanzetta & Bowen 1992; Steidel, Dickinson, & Persson 1994a) are now generally considered to indicate some kind of rather extended halos of disk galaxies or proto-galaxies, with radii of order 50 kpc and fairly metal-rich, but the high column density LLS presumably come from inner proto-disks. The nature of the more plentyful Ly-α forest is still controversial, but the metal abundance is lower (although probably above $Z \sim 10^{-4}$) even at large redshifts (Lu 1991). Recent observations have suggested very large sizes for high redshift "forest clouds", 40 to 400 kpc (e.g. Bechtold *et al.* 1994), and also large extensions around ordinary galaxies at lower redshifts. Self gravity and temperatures $< 2 \times 10^4 K$ ensure that cloud scale-heights are much less than the total radius of the extension (see, e.g. Charlton *et al.* 1994). Although much of the absorption at $z < 1$ is directly associated with ordinary, visible galaxies, an appreciable (but controversial) fraction comes from invisible objects (possibly 80%; see e.g. Mo & Morris 1994). These invisible objects can be the "vanishing Cheshire Cat" galaxies, discussed below.

The main postulate for protogalaxies of the "vanishing Cheshire Cat" type (Salpeter 1993) is that they were qualitatively similar to ordinary disk galaxies (including large, but low-density, gas extensions), but with a smaller maximum value $N_{max} \sim 10^{21.5}$ cm^{-2} of the initial disk gas column density, and smaller rotational velocity V_r. The ratio of dark matter to gas (parametrized in Section 2) is not specified but is probably comparable to the ratio for ordinary galaxies. Because of the scaling of column densities, the gravitational escape velocity is smaller than for an ordinary galaxy with the same radial scalelength. Recent observations (Salpeter & Hoffman 1995) suggest that these anemic galaxies occur in association with ordinary galaxies as members of a loose galaxy group or as satellites of a large ordinary galaxy.

Consider now the inner disk in three different types of protogalaxies: (*i*) ordinary spiral galaxies with $V_r \sim 200$ km s^{-1}, an escape velocity slightly larger, and a maximum baryon disk column density $N_{max} \sim 10^{22.5}$ cm^{-2}; (*ii*) dwarf irregular galaxies with N_{max} only slightly smaller (Lo 1993) but V_r much smaller (30 to 80 km s^{-1}) and (*iii*) the putative "Cheshire Cat", anemic galaxies. As discussed in Section 2, we assume that a metal abundance of $Z \sim$ (1 to 3) $\times 10^{-4}$ solar was already present at a very early epoch in all

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protogalaxies. We then find that ordinary spiral galaxies with large V_r were "doubly safe" in starting star formation early : (a) as seen in Figure 3 for large column densities the required metal abundance for the HI to start cooling to the cool phase is lower and the phase transition can start at a higher redshift, even if it proceeds slowly until Z increases to about the value of Z_{min} (Figure 4). (b) With dark matter not very important in the inner disk and with $V_r > 100$ km s^{-1}, eq.[2.7] shows that gravitational instability could set in even if the HI were still in the warm phase. Moreover with $V_{esc} > V_r$ and large, even a substantial starburst is not likely to lead to a galactic wind.

The situation is different for disks with small V_r and V_{esc}, i.e. both dwarf irregulars and the postulated anemic protogalaxies; especially for the latter where the central column densities are even smaller. As seen in Figure 4, for $N_{HI} \lesssim 10^{21}$ cm^{-2} cooling below the warm phase at $z \sim 1$ requires $Z \gtrsim 0.001$ which implies some metal enrichment in the disk. Although we don't know N_{dm}/N_g in these galaxies, it is likely that the gravitational instability (eq.[2.7]) sets in strongly only when the transition to the cold phase, which for these galaxies happens very fast, lowers v_s by about a factor 10. The gravitational instability triggers star formation (Kennicutt 1989; van der Hulst *et al.* 1993; Taylor *et al.* 1994; Dopita & Ryder 1994) and as star formation starts in some areas, it increases Z and speeds up the transition to the cool phase for surrounding regions. It is difficult to be more quantitative since this happens at a later epoch, when the background flux is already decreasing with time and this condition favors the transition to the cool phase and the starbursts. But there is another effect which goes in the opposite direction: bulk motions which are setup by the starburst, contribute to the increasing of the overall velocity dispersion and may counteract the decrease in the atomic thermal speed.

The concluding remark is that the postulated smaller N_{max} favors the delay of the onset of extensive star formation and the identification of the anemic proto-disk in the starburst phase with the "faint blue galaxies" seen at $z \sim 0.5$. The slightly smaller central column density and/or smaller escape velocity than in ordinary dwarf irregular galaxies should be sufficient to decrease the column density of the inner disk appreciably during the starburst phase (the vanishing of the cat body) by a galactic wind and/or fountain. As a consequence these galaxies become fainter, to the point that they may seem to have faded away from $z \sim 0.5$ to now, in agreement with the decreasing number of "faint blue galaxies" observed from $z \sim 0.5$ to now. The gas mass in the outer disk, where no star formation takes place, is unaffected by the runaway or even increased by a fountain (i.e. the smile of the

cat remains or is intensified) and originates absorption lines in the surroundings of these today's invisible galaxies.

4. SUMMARY AND DISCUSSION

We have discussed an intermediate phase in the evolution of protogalaxies which takes places after the hydrogen has recombined and a circular disk has formed but before the first substantial burst of star formation. This phase is regulated by the slow decrease in time of the extragalactic ionizing photon flux and by the slow increase of the heavy element abundance Z in the ISM due to contamination from sporadic, small-scale star formation elsewhere in the disk (possibly due to interaction with minor satellites). In particular we have calculated the minimum value Z_{min} which must be exceeded for the HI in the disk to cool from the warm phase to the cool phase in a small fraction of the Hubble time. Values of Z_{min} are given in Fig. 4, as a function of the total neutral hydrogen column density N_{HI} normal to the galactic disk. Z_{min} decreases slowly with decreasing redshift z and depends on the intensity of the background at a fixed z and somewhat on the dark matter parameter η. The most important feature is however its rapid decrease with increasing N_{HI}.

Disregarding the innermost part of disk galaxies, which may be affected by nuclear activity, we focus on the inner galactic disk where the average column density N_{HI} is 0.1 to 0.3 its initial maximum central value and where the first large scale starburst is likely to occur. We are particularly interested in the evolutionary fate of possible anemic protogalactic disks (which might be either a separate class of galaxies or merely an extension of dwarf irregulars and/or Malin objects) in contrast with the fate of large spirals. We postulated that their column density is slightly smaller than for irregular galaxies which in turn is smaller than the initial column density of today's spiral galaxies ($\sim 10^{22}$ to $10^{22.5}$ cm^{-2}). Assuming $V_r < 100$ km s^{-1} for "anemics" as it is for dwarf irregular galaxies, the initial cooling of the ionized hydrogen down to $\sim 3 \times 10^4$ K, say, was rapid but because of the small N_{HI} and the consequent better penetration of the extragalactic UV flux, the H-recombination was slow (Babul & Rees 1992; Efstathiou 1992). We have shown that these objects experience a further time delay for cooling to temperatures below 100 K because they require the infusion of more metals. If one assumes that contamination gave

$Z_{init} \sim 10^{-4}$ to 10^{-3} in all disks (Lu 1991; Spite & Spite 1992) before local star formation, one contrast is seen immediately from Fig. 4: large spirals had $Z_{min} < Z_{init}$ even at the largest redshifts, whereas $Z_{min} \gg Z_{init}$ even today ($z = 0$) for the anemic proto-disks. As shown by eq. [2.7] the small rotational velocity in low column density objects may inhibit large scale star formation while the gas is in the warm phase. Here again there is a contrast between normal spirals with large V_r, where instability can set in easily even when the sound speed is large, and dwarf irregulars or "anemics" for which gravitational instability might set in only after a slow build-up of metals, when the gas is in the cool phase and the sound speed becomes 10 times smaller than in the warm phase.

Cohen *et al.* (1994) have found an HI disk at $z \approx 0.69$ with a gas temperature $T > 1000K$ (well above the cool phase temperature) with a metal abundance $Z \sim (0.01$ to $0.1)$ and an observed column density $N_{HI}/\cos i = 2 \times 10^{21}$ cm^{-2} where i is the disk inclination angle. The warm temperature of the ISM can be due to star formation already present in the disk, but we can also use Fig. 4 to ask whether - as an alternative model - the HI may not yet have made the transition from the warm to the cool phase. As an example take $Z = 0.03$: for large values of J_0, $J_0 = 5$, and $\eta \ll 1$ we would need $N_{HI} < 4 \times 10^{20}$ cm^{-2}, to give $Z_{min} > Z$ i.e. $\cos i$ would have to be less than 0.2 for the HI disk to still be in the warm phase, before the onset of massive star formation. Such a small $\cos i$ may seem unlikely, but the actual value is uncertain because of the uncertainties in Z. Steidel *et al.* (1994b) have some optical data which argues against the presence of many stars: they find a very small upper limit to optical surface brightness in the immediate vicinity of the quasar line of sight where $N_{HI}/\cos i$ has been measured (although a LSB galaxy is visible about 15 kpc away).

The transition to the cool phase for anemic galaxies starts later but proceeds fast since $N_{HI} < N_*$. When an isolated protogalaxy has the HI in its cool phase star formation may start more easily not only because is gravitationally more unstable but because the Jeans mass is lower, and furthermore cool temperatures facilitate molecule formation. In these galaxies the overall conditions are such that the first occurrence of instability, fragmentation and formation of massive stars may lead to a "run-away violent starburst", described in detail in Section 4. The likely galactic winds or fountains decreases the gas content of the inner disk sufficiently to shut off further star formation and the increase of metal content. We have dubbed extreme cases of this kind "Cheshire Cat" galaxies (Salpeter 1993; Salpeter & Hoffman 1995) where the inner disk (body) fades to almost

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invisibility while the low-density outer disk (smile) remains (or is even enhanced by an outer fountain; Bregman 1980; Corbelli & Salpeter 1988).

The less drastic version of anemic galaxies may already explain the "evolution puzzle" for the faint blue objects (e.g. Koo & Kron 1992): the evolution seems puzzling in the context of normal, large spiral galaxies where the onset of star formation occurred early, $z > 1$, and gave a high onset luminosity with rapid initial fading, but slow luminosity changes subsequently, i.e. little fading on the average from $z \sim 0.5$ to now. The faint blue objects instead seems to have experienced a late burst of star formation and to have been more common at modest redshifts, $z \sim 0.5$, than now. We propose that since anemic galaxies had their first starburst later, because of their delay in HI cooling and in reaching the condition for gravitational instability, they could be identified with the faint blue objects which then fade into very low luminosity dwarf irregular galaxies because of the mass loss driven by the delayed violent starburst. To explain the optical fading alone a small mass loss would be sufficient, but some data on high column density Lyman Limit systems at low redshift (Storrie-Lombardi *et al.* 1994) may point to more drastic mass loss from inner disks of anemic galaxies. In fact, while at high redshifts an appreciable fraction of LLS have $N_{HI} > 2 \times 10^{18}$ cm^{-2} and presumably come from inner proto-disks, for $z < 1$ very few LLS have $N_{HI} > 2 \times 10^{18}$ cm^{-2} (see Table 2 of Salpeter & Hoffman 1995), which may indicate that gas content of most anemic inner disks decreased below $\sim 2 \times 10^{18}$ cm^{-2}.

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FIGURE CAPTIONS

Figure 1. Equilibrium curves for a slab of fixed metallicity (Z=0.01 solar) and HI column density of gas (upper curve $N_{HI} = 3 \times 10^{20}$ cm^{-2}, lower curve $N_{HI} = 3 \times 10^{21}$ cm^{-2}). The vertical axis increases downward and give the required ratio of $J_0(1+\bar{z})^3/(1+\eta)$ in order to have an equilibrium temperature T. The two thermally stable phase (cool and warm phase) have a negative slope in the graph. The open circle indicates the lowest stable temperature for the warm phase, called "transition point" in the text.

Figure 2. Given a perturbation on the metallicity at the transition point, $\delta Z/Z_{tr} = 1$, we show for a given value of z, J_0, and $\eta \ll 1$, the time evolution of $\delta T/T_{tr} \equiv (T - T_{tr})/T_{tr}$ from the warm to the cold phase. Time has been normalized to the Hubble time, t_H.

Figure 3. For a fixed value of z, J_0, and $\eta \ll 1$, in (a) we show the time required to complete the transition between the warm and the cool phase, as a function of N_{HI}, given a perturbation on the metallicity of fixed amplitude, $\delta Z/Z_{tr} = 1$. Time has been normalized to the Hubble time, t_H. The open circle indicates tha case shown in detail in Figure 2. In (b) for the same value of z, J_0, and η we plot Z_{tr} (light curve) and Z_{min} (heavy curve). The star indicates the column density for which $t = 0.2t_H$ in (a) and $Z_{min} = 2Z_{tr}$ in (b).

Figure 4. For 3 different combination of J_0 and η, we give Z_{min} as function of N_{HI}. Continuous curves are for $z = 2.5$, dotted curves are for $z = 1$ and dashed curves are for $z = 0.1$. In each plot and for the three values of the redshifts the star indicates the column density N_* for which $Z_{min} = 2Z_{tr}$. For $N_{HI} < N_*$ a slight excess of Z above Z_{tr} ensures that the transition to the cool phase proceeds rapidly.